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End forming of thin-walled tubes

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Abstract

The term ‘end forming of tubes’ is commonly used to describe the production of simple or complex tube end shapes by means of a wide variety of processes such as expansion, reduction, inversion, flaring, flanging and tapering.

This paper is the result of a numerical and experimental investigation on the field of expansion and reduction of thin-walled tubes using a die with the objective of dealing with existing gaps in knowledge related to the influence of process parameters on the formability limits induced by ductile fracture, wrinkling and local buckling. The numerical investigation is accomplished by the use of virtual prototyping modelling techniques based on the finite element method and the experimental investigation was performed on tubular components of AA6060 Aluminium alloy, under laboratory-controlled conditions with the purpose of supporting and validating the theoretical investigation.

Keywords: End forming of tubes; Finite element method; Experimentation

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1. Introduction

End-forming of thin-walled tubes by means of expansion and reduction is accomplished by forcing a tapered, dedicated punch (or die) into the tube end, and then retracting the punch (or die) back off after achieving the desired shape (Fig. 1). The expansion punch is dedicated to an outside radius r_p and a required length of expansion whereas the reduction die is dedicated to an inside radius r_d and a required length of reduction. The lengths of expansion and reduction depend on the angle of inclination α and the design of each tooling is a function of the initial reference radius r_0 of the tubes. Both processes comprise three different plastic deformation mechanisms; (i) bending/unbending, (ii) stretching (or compression) along the circumferential direction θ and (iii) friction. The later is mostly active during the deformation of the tube over the punch (or die).

In the past years, investigation trends in the field of end forming of tubes have been mainly focused on the inversion forming of thin-walled tubes using a die [1–4]. As a result of this, actual design rules for expansion and reduction are mainly derived from the accumulated experience of both manufacturers of tubular parts and suppliers of machine-tools. No systematic studies exist, as far as authors are aware, on the influence of process parameters on material flow and in providing an adequate description of the deformation modes associated with the formability limits induced by ductile fracture, wrinkling and local buckling.

The above mentioned topics are crucial for accomplishing an adequate characterization of the different modes of deformation, for successfully predicting the geometrical profiles found in daily practice and for reducing the degree of uncertainty that is frequently introduced in finite element models by means of pertinent assumptions in terms of friction and ductile fracture. This paper is aimed to find answers to some of the above mentioned gaps of knowledge.

2. Experimental background

2.1. Mechanical, tribological and formability characterization

The material employed in the experimental tests was an AA6060 Aluminium alloy (natural aged). The stress–strain curve was obtained by means of tensile and compression tests carried out at room temperature,

$$\bar{\sigma} = 298.3\bar{\varepsilon}^{0.09}\ \text{MPa} \tag{1}$$

The tribological conditions at the contact interface between the tube and the tools were estimated by means of ring compression tests on ring test samples (6:3:2 proportions) prepared according to the lubrication procedure utilized in the forming process (MoS_2 based lubricant). Interface friction was characterized by means of the law of constant friction, $\tau = mk$ and the friction factor m was

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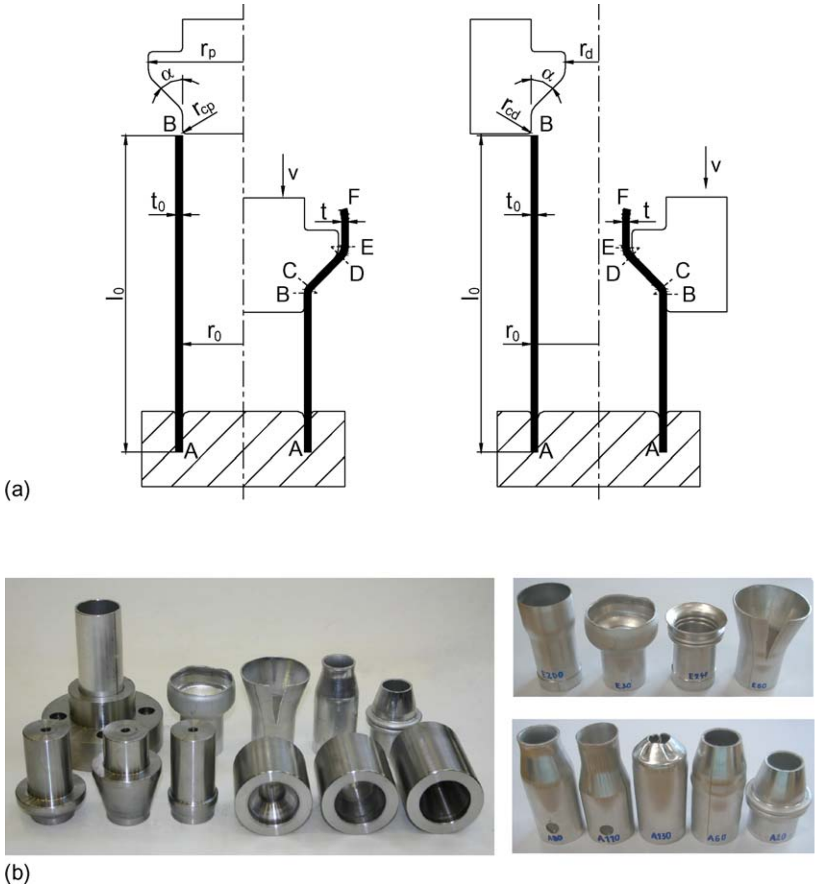

Fig. 1. Expansion and reduction of thin-walled tubes using a die. (a) Schematic representation of both processes. (b) Active tool components and samples of successful and unsuccessful tubular parts.

found to be equal to 0.11 according to calibration curves determined by finite element simulation.

The experimental procedure utilized to characterize the formability of the Al6060 Aluminium alloy was based on the evaluation of fracture strains of cylindrical upset tests specimens ($h/d = 2.5$) as suggested in [5]. A critical alue of damage of 0.42 was obtained for the normalized Cockcroft–Latham criterion. No lubricant was utilised during the upset formability tests.

2.2. Experimental procedure

The experiments were performed on tubular specimens with a reference radius $r_0 = 18$ mm (tube expansion) and $r_0 = 20$ mm (tube reduction), and two different values of the wall thickness, $t_0 = 1.0$ and 2.0 mm. The length of the tubes was $l_0 = 90$ mm. The experiments were performed at a displacement rate of 1.17 mm/s and, therefore, no dynamic effects in the deformation mechanics of the tubes were taken into account.

The plan of experiments was set up in order to consider the main parameters that govern the expansion and reduction processes; (i) the ratio r_p/r_0 (1.25, 1.39, 1.53 and 1.67 for expansion) and r_d/r_0 (0.5, 0.625, 0.75 and 0.875 for reduction), (ii) the ratio t_0/r_0 (0.055 and 0.111 for expansion; 0.05 and 0.1 for reduction), (iii) the angle α (15°, 30° and 45°) of the conical surface of the punch (or die) and (iv) lubrication (MoS_2 and dry conditions), (Fig. 1).

In order to allow load recording during experiments, force was applied to the punch (or die) through one load cell based on traditional strain-gauge technology in a full Wheatstone bridge. Displacements were measured using a micro-pulse position transducer. An electronic board and Windows based software were utilized for performing data acquisition directly from the previous mentioned equipments.

3. Theoretical background

The expansion and reduction of thin-walled tubes using a die were analysed by means of the computer programs I-FORM2 and I-FORM3. The programs are based on the irreducible finite element flow formulation which relies on the minimization of the following variational statement,

$$\pi = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}\,\mathrm{d}V + \frac{1}{2}K\int_V \dot{\varepsilon}_\mathrm{v}^2\,\mathrm{d}V - \int_{S_\mathrm{T}} T_i u_i\,\mathrm{d}S \tag{2}$$

where, K is a large positive constant enforcing the incompressibility constraint and V is the control volume limited by the surfaces S_U and S_T, where velocity and traction are prescribed, respectively. The role of friction is added in (2) by means of the law of constant friction, $\tau = mk$. Thus, assuming friction to be a traction boundary condition, the extra power consumption term π_f due to friction can be expressed as,

$$\pi_\mathrm{f} = \int_{S_\mathrm{f}} \left(\int_0^{|u_\mathrm{r}|} \tau_\mathrm{f}\,\mathrm{d}u_\mathrm{r} \right) \mathrm{d}S \tag{3}$$

where, S_f is the contact interface, u_r is the relative velocity and, τ_f is the friction shear stress between the tube and tooling. Further details on the computer implementation of the flow formulation and friction modelling can be found elsewhere [6].

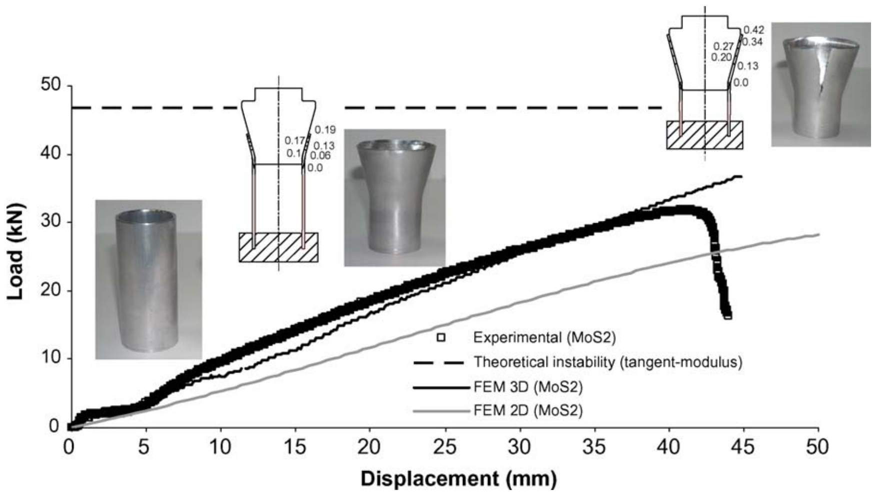

Fig. 2. Numerical and experimental evolution of the load–displacement curve for the expansion of thin-walled tubes ($t_0 = 2.0$ mm, $r_p/r_0 = 1.76$ and $\alpha = 15°$). Insets show the distribution of the normalized Cockcroft–Latham ductile damage criterion.

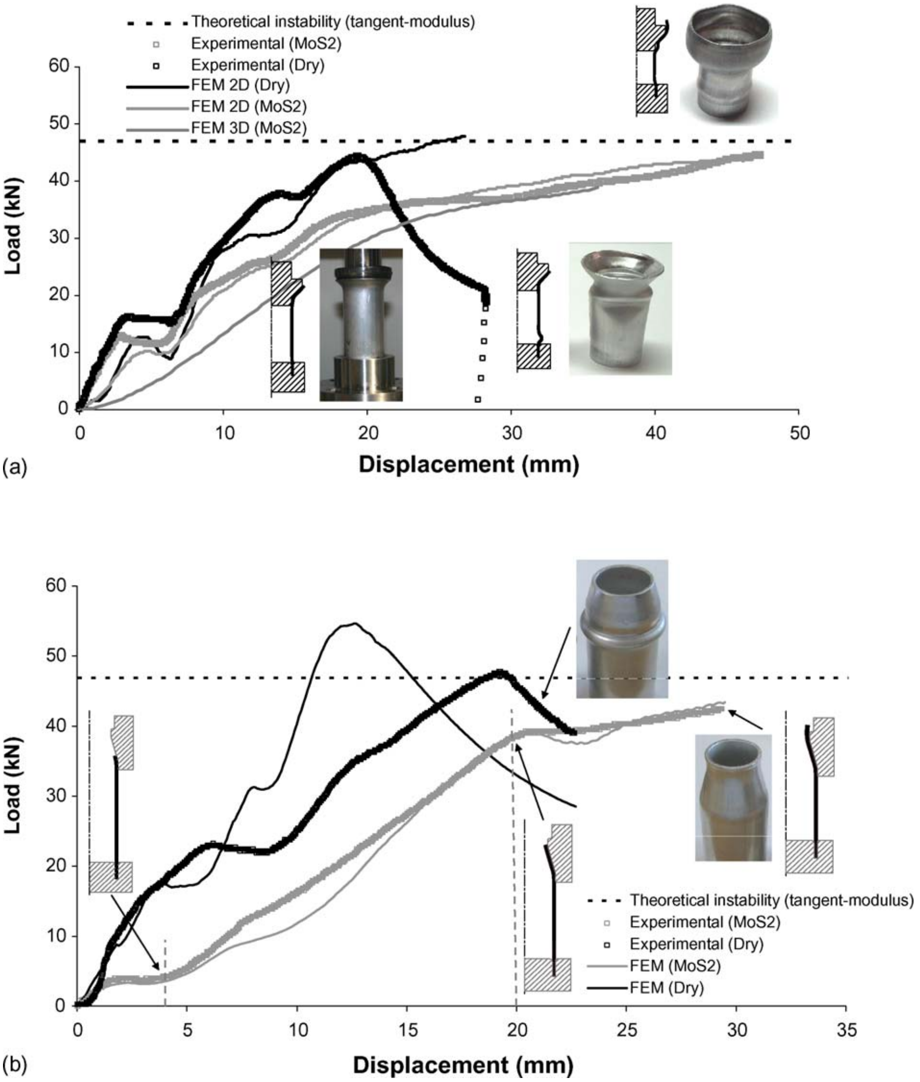

Fig. 3. Theoretical and experimental evolution of the load–displacement curve. (a) Expansion of a tube with $t_0 = 2.0$ mm, $r_p/r_0 = 1.76$ and. (b) Reduction of a tube with $t_0 = 2.0$ mm, $r_d/r_0 = 0.75$ and $\alpha = 15°$.

Three-dimensional finite element computer models planned in accordance to the experimental data were set-up to reproduce the observed modes of deformation. The discretization of the tubes was performed by means of structured meshes of hexahedral elements while the tools were discretized by the use of contact-friction linear triangular elements. On account of rotational symmetry of some of the observed modes of deformation alternative two-dimensional models, in which the initial cross section of the tubes was discretized by means of axisymmetric quadrilateral elements and the contour of the dies by means of contact-friction linear elements, were also employed.

4. Results and discussion

The critical plastic instability for the occurrence of local buckling ($P_{\mathrm{cr}} = 21.5$ and 46.8 kN for tubular wall thicknesses of $t_0 = 1.0$ and 2.0 mm, respectively) was obtained by axial compressing the tubes between flat dies [3].

4.1. Formability limits

The work on tube expansion confirmed the existence of three different modes of deformation (Fig. 1). For large ratios of r_{p}/r_0 (radius of the punch/initial radius of the tube) and high values of α (angle of inclination), formability is limited by the occurrence of plastic instability (local buckling) while for larger lengths of expansion restrictions are normally set by ductile damage in the regions that are highly stretched in the circumferential direction. The work on tube reduction also revealed the existence of three different modes of deformation. For small values of r_{d}/r_0 and small lengths of reduction (high values of the angle α) formability is mainly limited by the development of plastic instability (local buckling) whilst for larger lengths of reduction restrictions are normally set by excessive thickening of the tube wall and by the occurrence of wrinkling at the conical wall.

Fig. 2 presents the experimental and numerical predicted evolution of the load–displacement curve for a tube expansion with $t_0 = 2.0$ mm, $r_{\mathrm{p}}/r_0 = 1.76$ and $\alpha = 15°$. Insets show pictures of tubular parts and the distribution of ductile damage at two different stages of deformation. An overall good agreement is found between finite element predictions and experimental results namely in what concerns the location and the level of deformation where crack initiation takes place $\left(\int_0^{\bar{\varepsilon}_f} \frac{\sigma_1}{\bar{\sigma}}\,\mathrm{d}\bar{\varepsilon} = 0.42\right)$.

Fig. 3 shows the experimental and numerical predicted evolution of the load–displacement curve for the expansion of a tube with $t_0 = 2.0$ mm, $r_{\mathrm{p}}/r_0 = 1.76$ and $\alpha = 45°$ (Fig. 3(a)) and for the reduction of a tube with $t_0 = 2.0$ mm, $r_{\mathrm{d}}/r_0 = 0.75$ and $\alpha = 15°$ (Fig. 3(b)). The curves present three different stages; (i) in the first stage the load increases steeply as the punch (or die) is forced into the tube, (ii) in the second stage the leading edge of the tube starts to flow along the conical surface of the punch (or die) and the load grows moderately from a lowered level, and (iii) the final stage begins after reaching the peak value of the forming load (the onset of instability $P_{\mathrm{f}} \cong P_{\mathrm{cr}}$) and is related to the occurrence of local buckling. The role of friction on the occurrence of local buckling is brought into evidence when the tubes are expanded/reduced under dry lubricated conditions.

4.2. Expansion of tubes into circular, elliptical and square cross sectional shapes

The case studies presented in this section were selected to show the potential of numerical modelling on the analysis of the formability limits of complex tube end forming operations. Three different final end-shapes were considered; (i) a circular (reference) shape with a diameter equal to 23 mm, (ii) an elliptical shape with major and minor axis respectively equal to 32 and

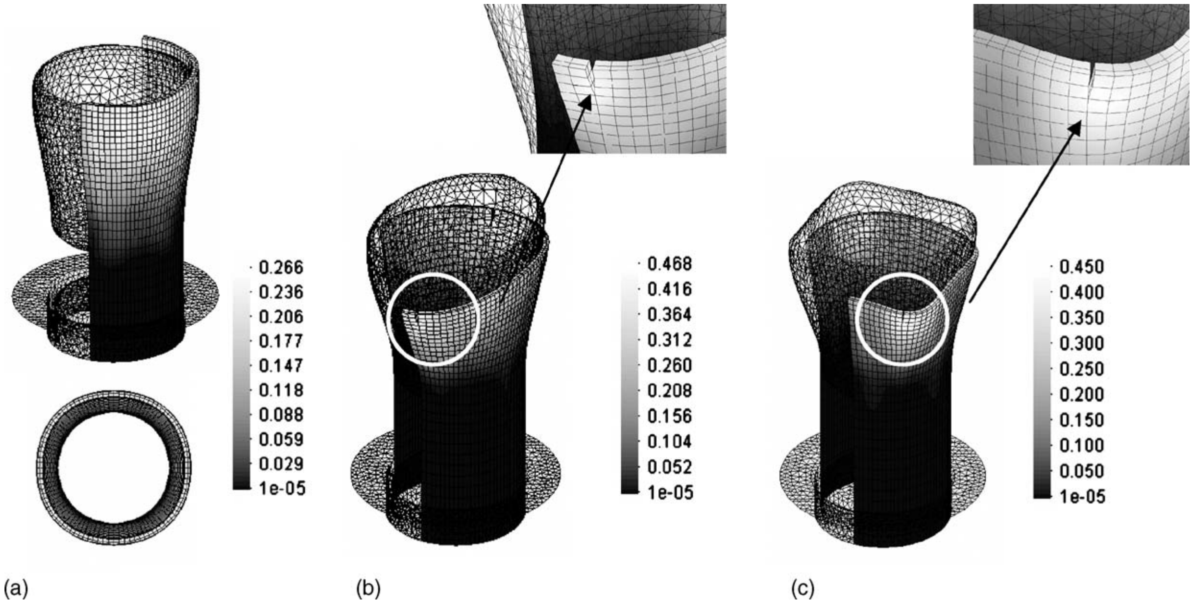

Fig. 4. Theoretical distribution of the normalized Cockcroft–Latham ductile damage criterion during the expansion of a tube into a circular, elliptical and square cross sectional hollow shape ($t_0 = 2.0$ mm). (a) $r_{\mathrm{p}}/r_0 = 1.28$. (b) Minor axis: $r_{\mathrm{p}}/r_0 = 1.28$, major axis: $r_{\mathrm{p}}/r_0 = 1.78$. (c) Edge and fillet corner radius respectively equal to 46 and 10 mm.

23 mm, and (iii) a square shape with 46 mm of edge and 10 mm of fillet radius (Fig. 4).

As can be concluded from the predicted distribution of damage, the circular shape can be successfully expanded without cracking because peak values are below the critical experimental value of 0.42 (Fig. 4(a)). On the contrary, expansion into elliptical and square cross sectional shapes will not be successfully accomplished due to the occurrence of ductile fracture. Cracks will propagate along the axial direction of the tubes, as shown in the details provided in Fig. 4.

5. Conclusions

The expansion and reduction of thin-walled tubes using a die is only achievable within a compact range of process parameters. The final radius, wall thickness, shape and length of the conical section of the tubes as well as the lubrication regime must be properly chosen so that material deformation does not approach any of the formability limits that are associated with ductile fracture, local buckling and wrinkling. Numerical modelling by means of the finite element flow formulation is adequate for understanding and predicting the various modes of deformation that can help engineers in designing tubular end parts in daily practice.

References

[1] S.R. Reid, Plastic deformation mechanisms in axially compressed metal tubes used as impact energy absorbers, Int. J. Mech. Sci. 35 (1993) 1035.

[2] G.S. Sekhon, N.K. Gupta, P.K. Gupta, An analysis of external inversion of round tubes, J. Mater. Proc. Technol. 133 (2003) 243.

[3] P.A.R. Rosa, J.M.C. Rodrigues, P.A.F. Martins, External inversion of thin-walled tubes using a die: experimental and theoretical investigation, Int. J. Mach. Tools Manuf. 43 (2003) 787.

[4] P.A.R. Rosa, J.M.C. Rodrigues, P.A.F. Martins, Internal inversion of thin-walled tubes using a die: experimental and theoretical investigation, Int. J. Mach. Tools Manuf. 44 (2004) 775.

[5] B.P.P.A. Gouveia, J.M.C. Rodrigues, P.A.F. Martins, Fracture prediction in bulk metal forming, Int. J. Mech. Sci. 38 (1996) 361.

[6] M.L. Alves, J.M.C. Rodrigues, P.A.F. Martins, Three-dimensional modelling of forging processes by the finite element flow formulation, J. Eng. Manuf. 218 (2004) 1695.